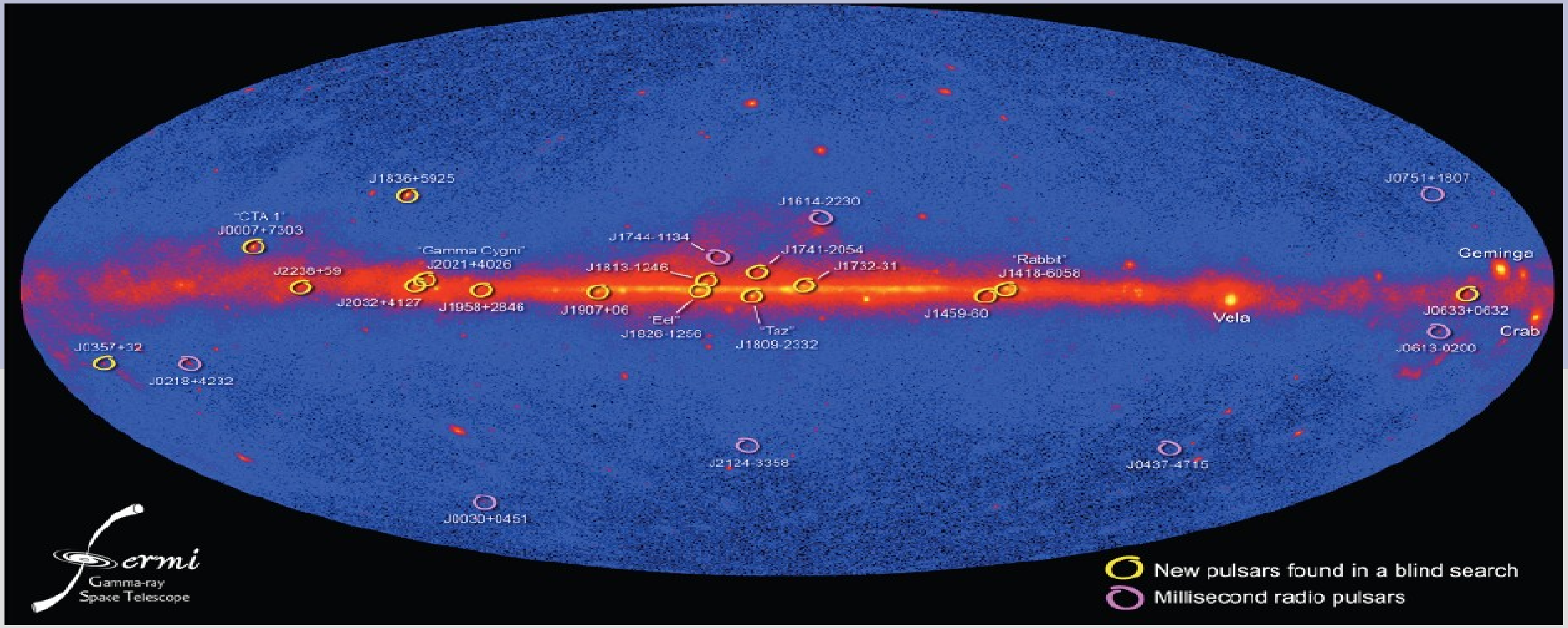
Monte Carlo simulation on population synthesis of γ-ray pulsars

Jumpei Takata
Yu Wang
K.S. Cheng
(University of Hong Kong)



Fermi γ-ray pulsars

Outline

1, Introduction

-Fermi γ-ray pulsars

-Population on canonical pulsars

2,A Monte-Carlo simulation

-γ-ray emission model (outer gap model)

3,Results

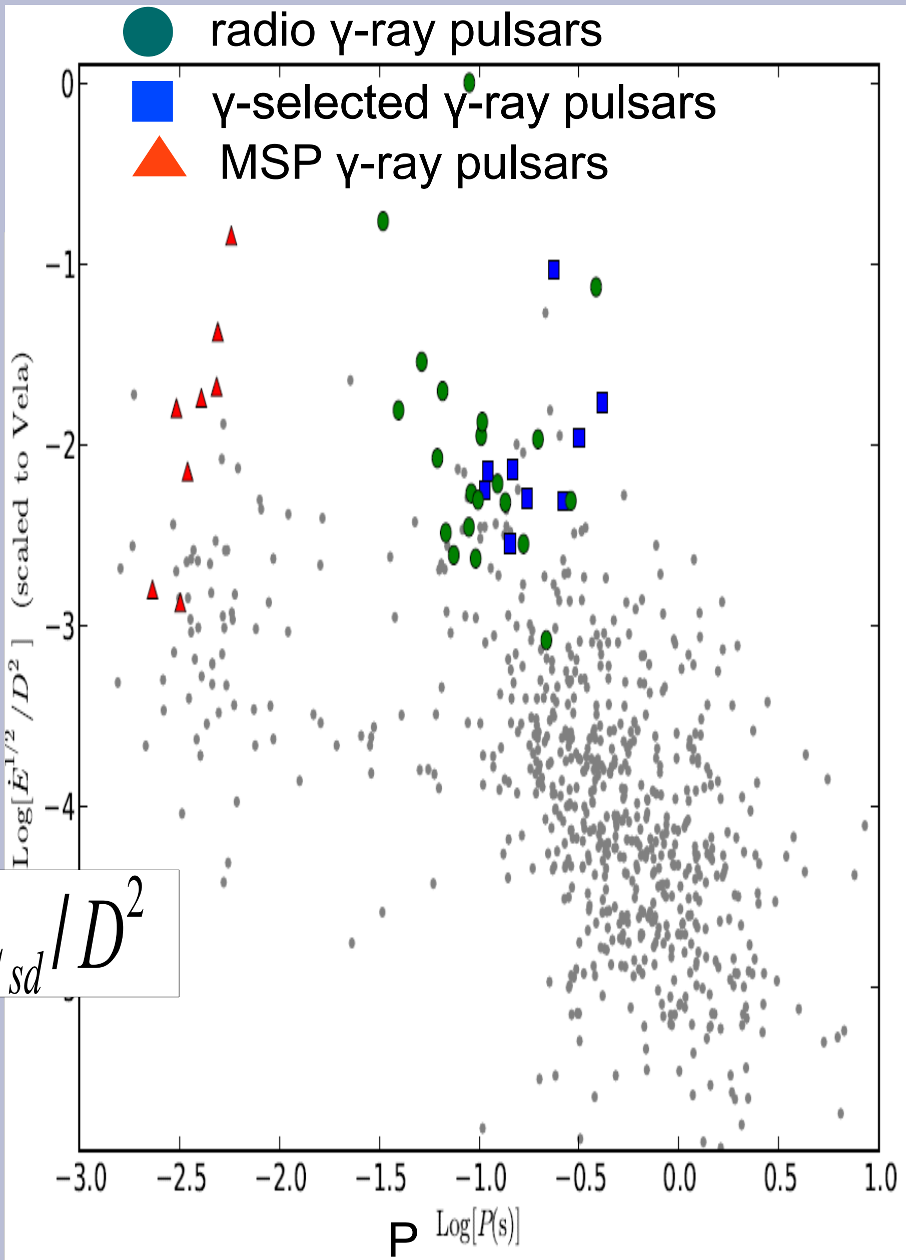
1, Introduction

Fermi γ-ray pulsars

- ***CGRO*** in 1990s discovered 7 γ-ray pulsars

- ***Fermi*** first pulsarcatalog reported 47 γ-ray pulsars (Abdo et al. 2010),
  (a)39 canonical pulsars
  -22 radio selected pulsars
  -17 γ-ray selected pulsars (including Geminga)
  (b) 8 millisecond pulsars
- And more....

Which pulsars can be seen by Fermi?



$$L_{sd}/D^2$$

The pulsar activity is caused by releasing the rotation energy (spin-down power).

$$L_{sd}=4\times10^{31}P^{-3}(\dot{P}/10^{-15})erg/s$$

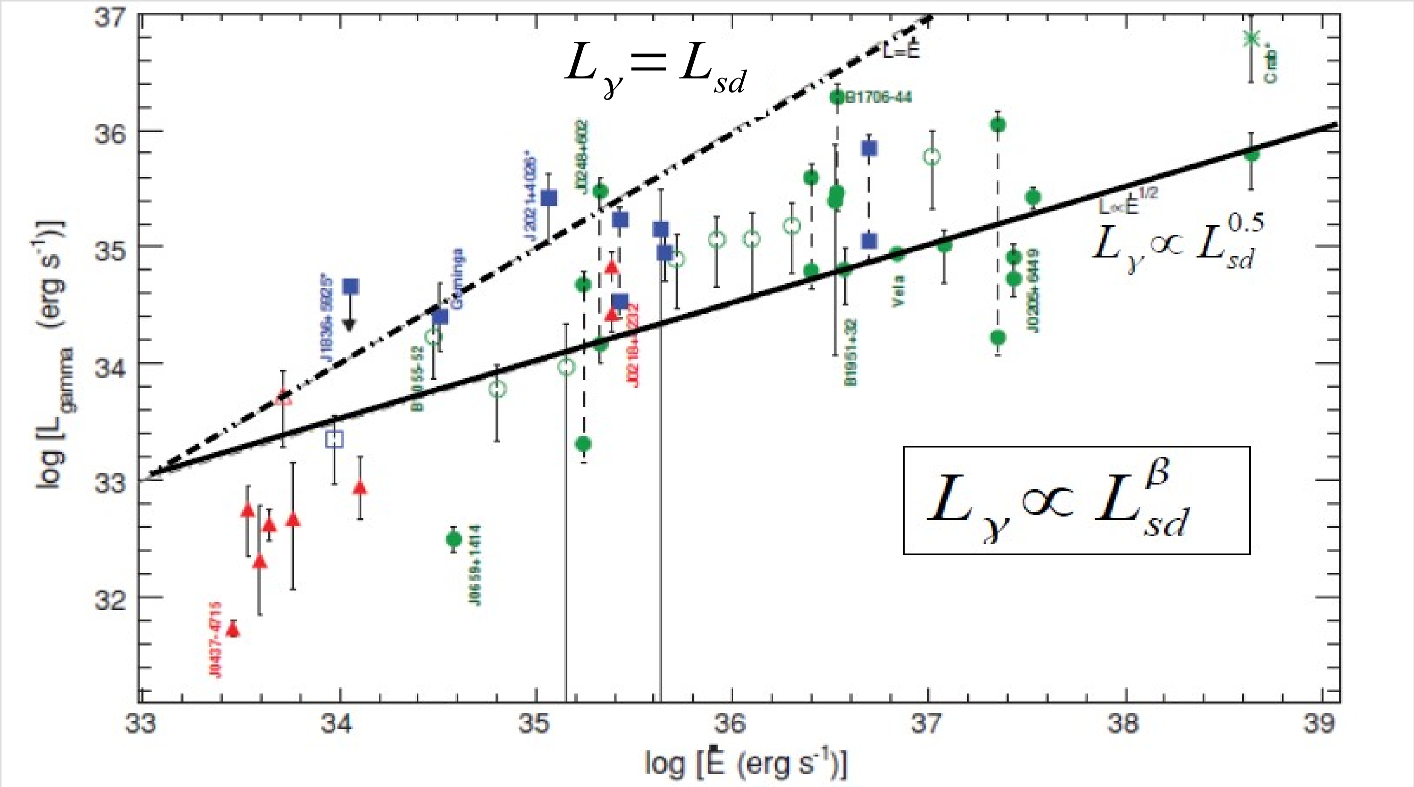
P; Rotation period

P-dot; Time derivative of rotation period

A fraction of spin down power is converted into γ-ray emissions.

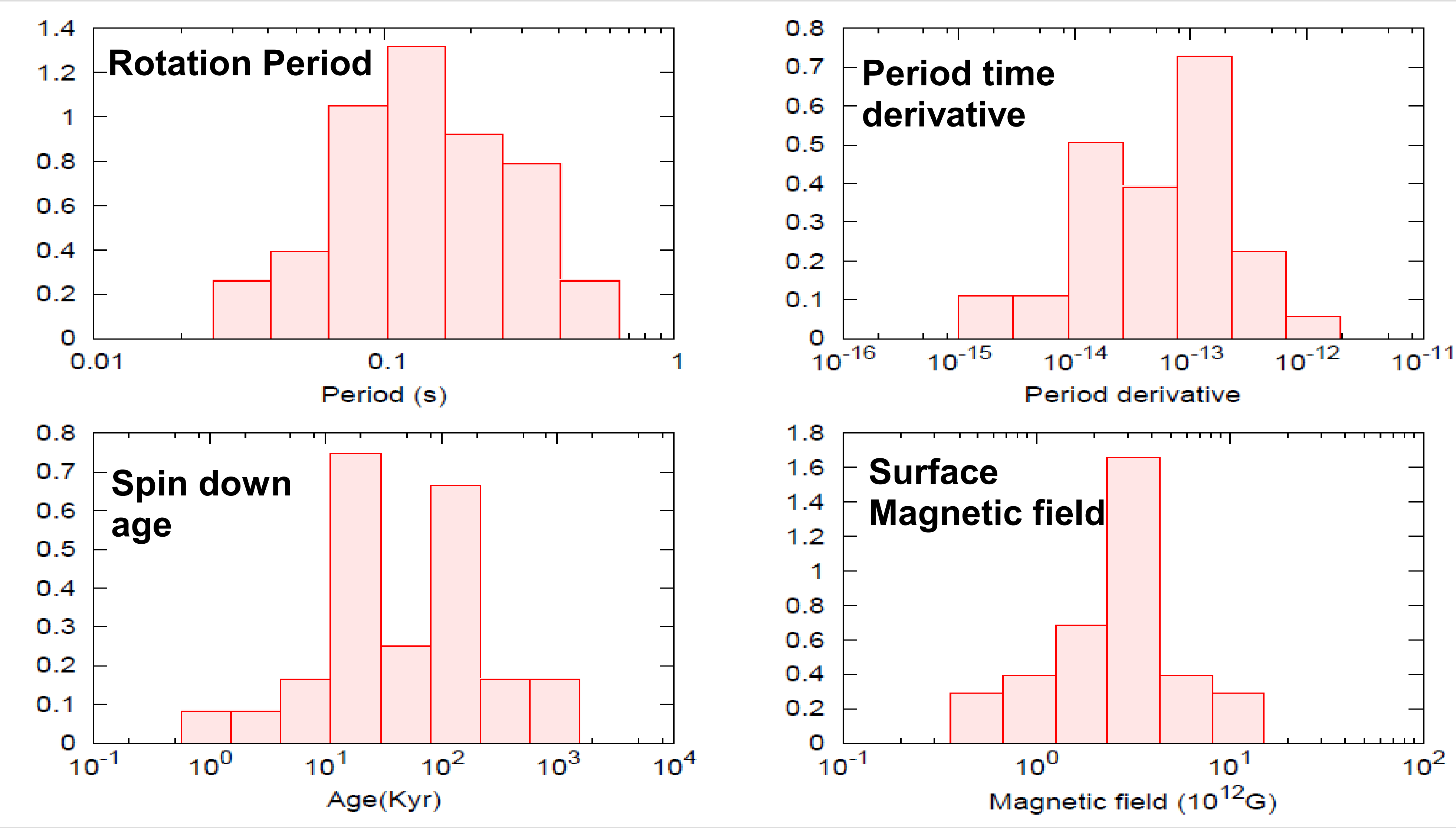
$$F_{\gamma}\propto L_{sd}/D^2$$

Population; Lγ vs. Lsd



β~0.5??, which was predicted by*CGRO*

Populations(canonical pulsars)



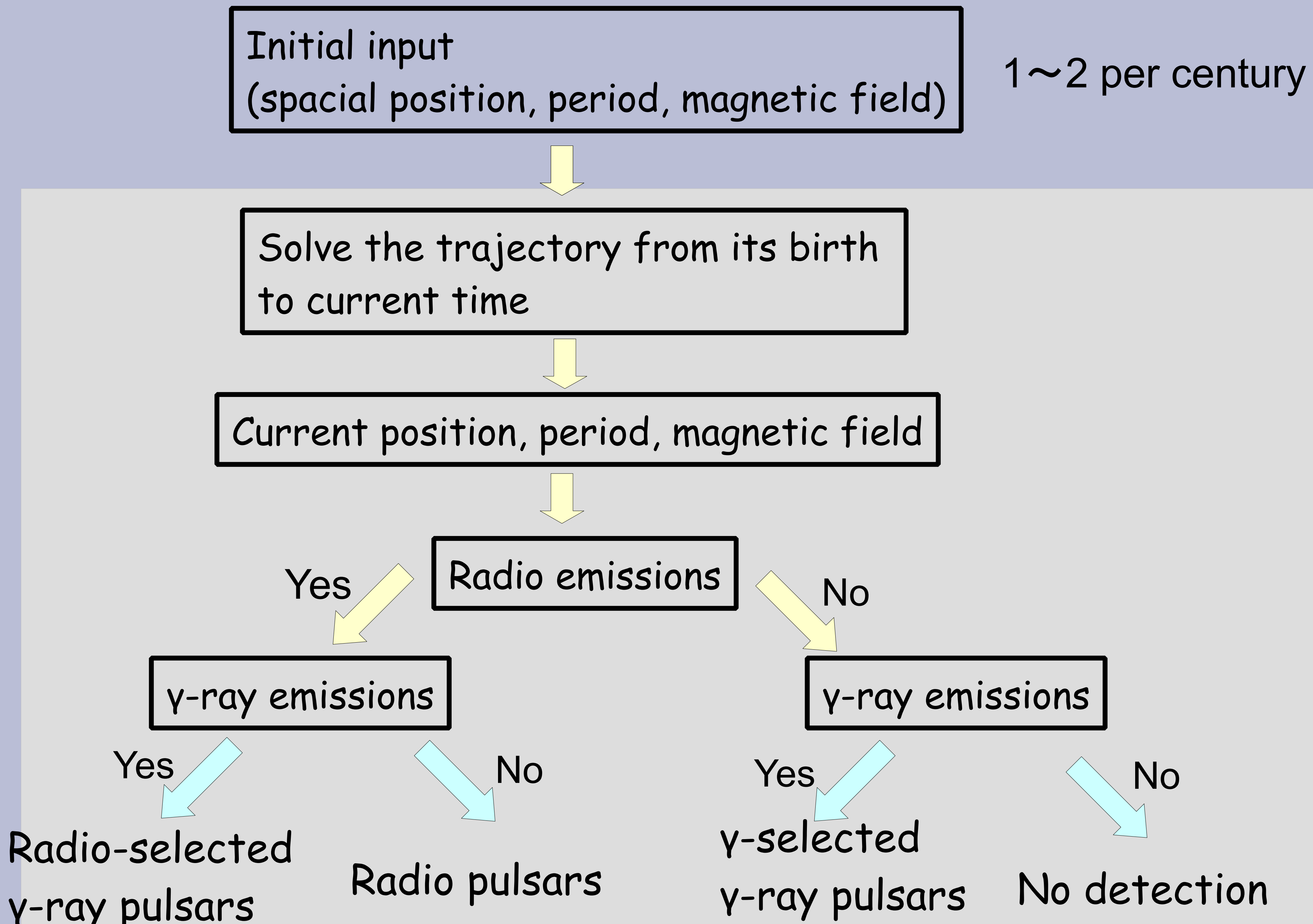
- ***Fermi*** can provide a more detail statistical properties of the γ-ray pulsars.

- Different emission models will predict different population.
- The observed population can be use to test the theoretical model.
- How many γ-ray pulsars will be found?

2, A Monte-Carlo Simulation

- A Monte Carlo simulation for the canonical γ-ray pulsars

- The simulated population is compared with the *Fermi* observations.


Initial input
(spacial position, period, magnetic field)
1～2 per century
Solve the trajectory from its birth to current time
Current position, period, magnetic field
Radio emissions
Yes
No
γ-ray emissions
γ-ray emissions
Yes
No
Yes
No
Radio-selected γ-ray pulsars
Radio pulsars
γ-selected γ-ray pulsars
No detection

Initial distribution

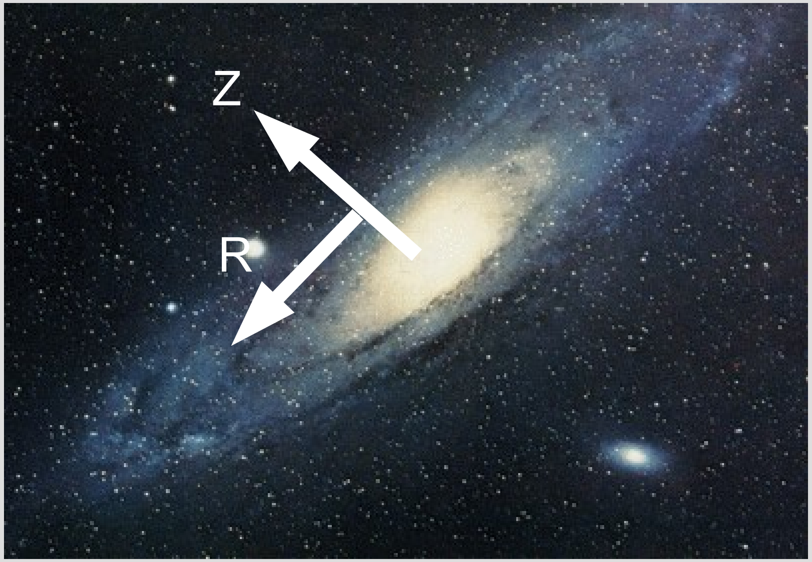
- Sturner & Dermer 1996
- Spacial distribution

(1) $$\rho_R(R) = \frac{a_R e^{-R/R_{\rm exp}} R}{R_{\rm exp}^2},$$

(2) $$\rho_z(z) = \frac{1}{z_{\rm exp}} e^{-|z|/z_{\rm exp}},$$

$a_R = 20$ kpc, $R_{\rm exp} = 4.5$ kpc

$z_{exp} = 75$ pc.



(3) Azimuthal direction; Random distribution with equal probability.

Initial distribution

- Velocity

  -Maxwell distribution with a width $\sigma_v = 265$ km/s,

$$\rho_v(v) = \sqrt{\frac{\pi}{2}}\frac{v^2}{\sigma_v^3}\mathrm{e}^{-v^2/2\sigma_v^2}.$$

- Rotation period; Pi=30ms
- Surface magnetic field

$\log_{10} B_0 = 12.6$ and $\sigma_B = 0.1$

$$\rho_B(\log_{10} B) = \frac{1}{\sqrt{2\pi}\sigma_B}\exp\left[-\frac{1}{2}\left(\frac{\log_{10} B - \log_{10} B_0}{\sigma_B}\right)^2\right],$$

Evolution

- Equation of motion (Paczynski 1990)

$$\frac{dR^2}{dt^2} = \frac{v_\phi^2}{R} - \frac{\partial \Phi_{tot}}{\partial R},$$

$$\frac{dz^2}{dt^2} = -\frac{\Phi_{tot}}{z},$$

$$R v_\phi = \mathrm{constant},$$

$$\Phi_i(R,z) = -\frac{GM_i}{\{R^2 + [a_i + (z^2 + b_i^2)^{1/2}]^2\}^{1/2}},$$

$$\Phi_h(r) = \frac{GM_c}{r_c}\left[\frac{1}{2}\ln\left(\frac{r^2}{r_c^2}\right) + \frac{r_c}{r}\tan^{-1}\left(\frac{r}{r_c}\right)\right],$$

(1) Disk component

$a_{dis} = 3.7$ kpc, $b_{dis} = 0.20$ kpc,

$M_{dis} = 8.07 \times 10^{10} M_\odot$

(2) Spheroid component

$a_{sph} = 0,\ b_{sph} = 0.277$ kpc

$M_{sph} = 1.12 \times 10^{10} M_\odot$

(3) Halo component

$r_c = 6.0$ kpc $M_c = 5.0 \times 10^{10} M_\odot$

We integrate the trajectory from its birth to current time (t=0).

Evolution

- Magnetic field

  -constant, τ<10Myr.

  -we will sample the neutron star younger than 10Myr.
- Period

  -Assuming dipole radiation

$$P(t) = \left(P_0 + \frac{16\pi^2 R_*^6 B^2}{3Ic^3} t \right),$$

- Period time derivative

$$\dot{P}(t) = \frac{8\pi^2 R_*^6 B^2}{3Ic^3 P}.$$

- Spin down age $\tau \equiv P/2\dot{P}$

Radio emission

- We empirically describe the radio luminosity at 400MHz as a function of P and P;

$$\rho_{L400}(P, \dot{P}) = 0.5\lambda^2 e^{-\lambda} \quad \lambda = 3.6[\log(L_{400}/\langle L_{400}\rangle) + 1.8]$$

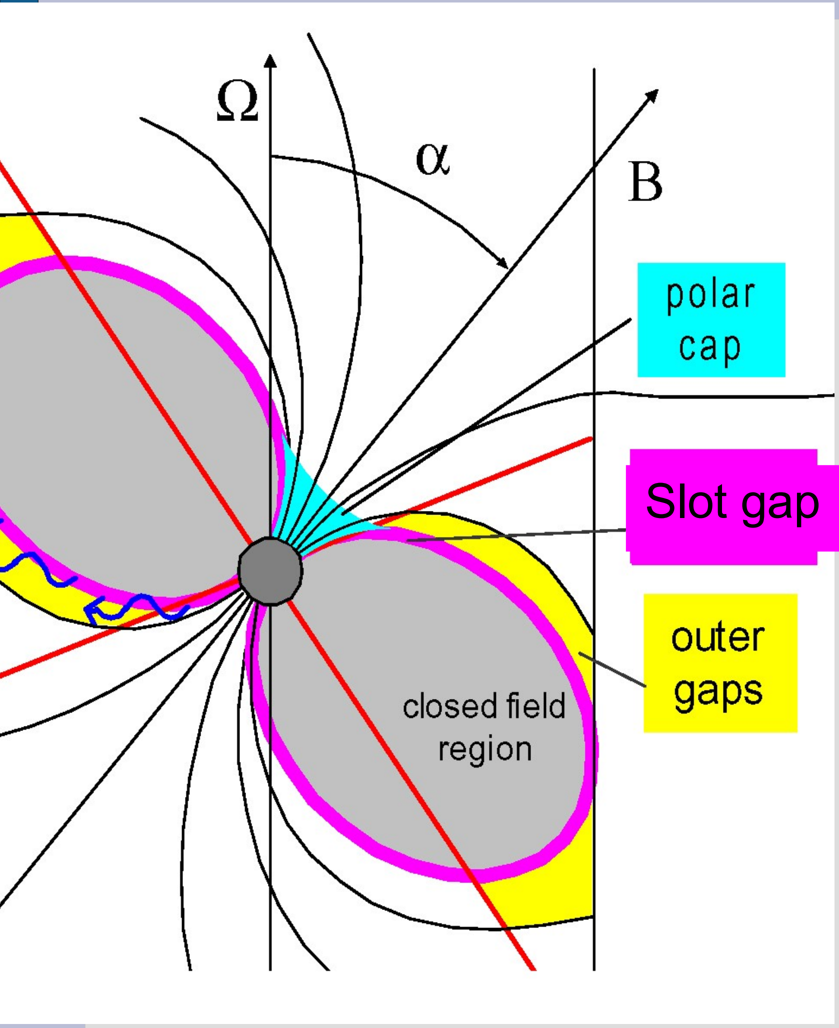
$$\log\langle L_{400}\rangle = 6.64 + \tfrac{1}{3}\log(\dot{P}/P^3)$$

- Detection L_{400}/D^2 >Smin   Smin; sensitivity
- Beaming effects (probability that radio beam point toward Earth or not)

$$f_r(\omega) = (1 - \cos\omega) + (\pi/2 - \omega)\sin\omega$$

Beam width (radius) $\omega = 0.02 r_{KG}^{1/2} P^{-1/2}$ $r_{KG} = 40\,\nu_{GHz}^{-0.26}\,\dot{P}_{-15}^{0.07}\,P^{0.3}$

γ -ray emission model



- Pulsar γ-ray emission model predicts

$$L_\gamma \simeq f^3 L_{sd}$$

- f≡Gap thickness/Size of magnetosphere (gap fractional thickness).
- The gap fractional thickness determines observed emission properties. (f is important factor)
- We investigate out gap model

Outer gap thickness model 1

- Zhang & Cheng (1997)
- Photon-photon process between the γ-rays and surface X-rays in the outer gap

$$E_X \sim 0.1 f^{1/4} B_{12}^{1/4} P^{-5/12} \mathrm{keV}$$

$$E_\gamma \sim 0.1 f^{3/2} B_{12}^{4/3} P^{-7/4} \mathrm{GeV}$$

- The pair-creation condition, $E_X \cdot E_\gamma = (m_e c^2)^2$ implies

$$f_{zc} \sim 5.5 \mathrm{B}_{12}^{-4/7} P^{26/21}$$

Outer gap thickness model 2

- Takata, Wang & Cheng (2010)
- The magnetic pair-creation process near the stellar surface.
- The pairs may affect the gap dynamics if the non-dipole field is strong enough

$$f_m \sim 0.8\, K\, P^{1/2} \qquad K \sim 1$$

- γ-ray luminosity & Flux

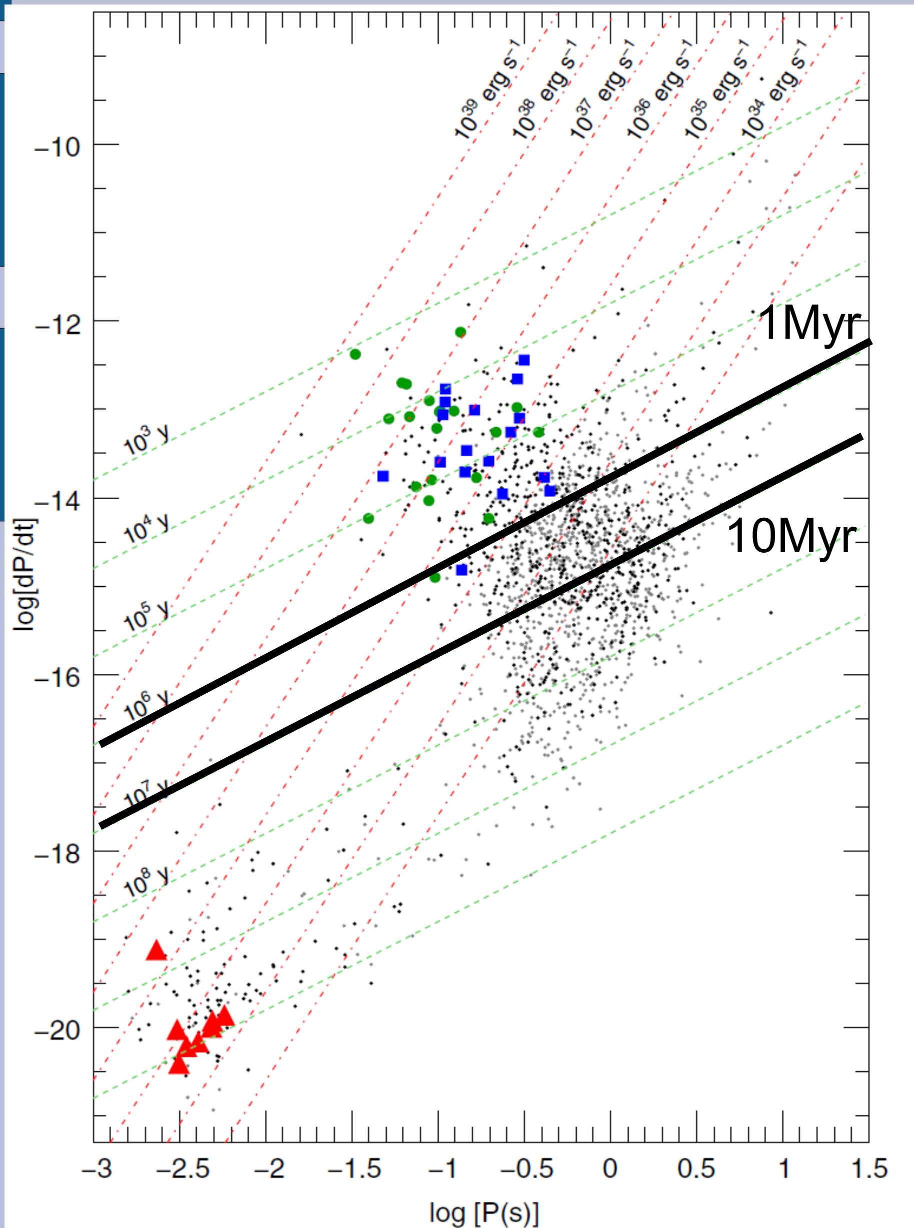
$$L_\gamma = f_{zc}^3 L_{sd} \qquad f_{ZC} < f_m \qquad F \sim \frac{L_\gamma}{\Delta\Omega\, d^2}$$

$$L_\gamma = f_m^3 L_{sd} \qquad f_m < f_{ZC}$$

$$\Delta\Omega = 1$$

3, Results

$\dot{P}$-P diagram

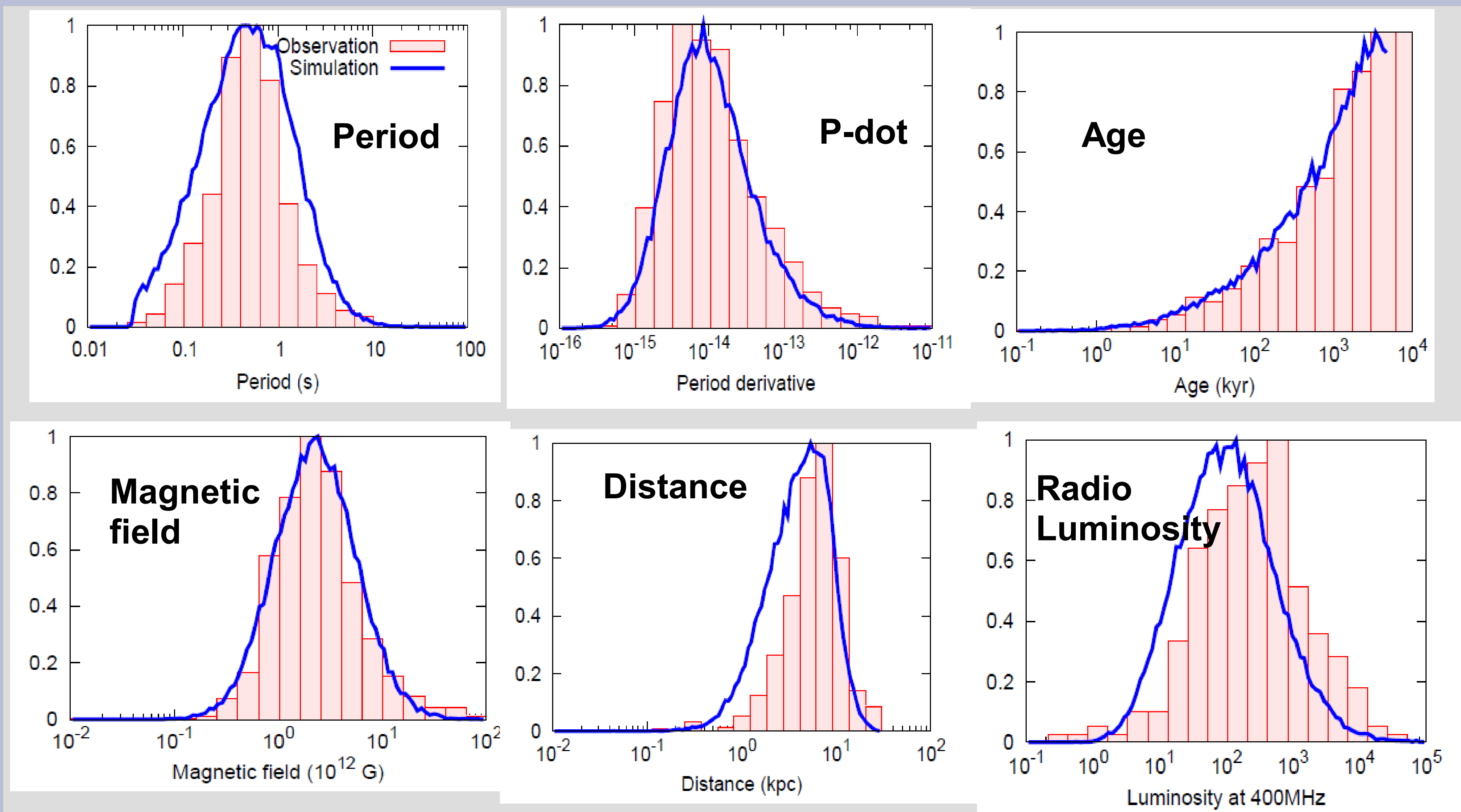


Sample of pulsars

- Canonical pulsars
- The Fermi γ-ray pulsars has spin-down age τ<2Myr.
- The simulation predict no detectable γ-ray emissions from canonical pulsars with τ>5Myr.

- We sample the pulsars with τ<5Myr.

Populations of the radio pulsars



Population of γ-ray pulsars

"Bright" γ-ray pulsars ($F>10^{-10}$ erg/cm^{2}s)

- **It is expected that most of the "bright" γ-ray pulsars have been already detected.**
- Observations ($F>10^{-10}$ erg/cm^{2}s);

  Radio-selected; 12

  γ-selected; 13

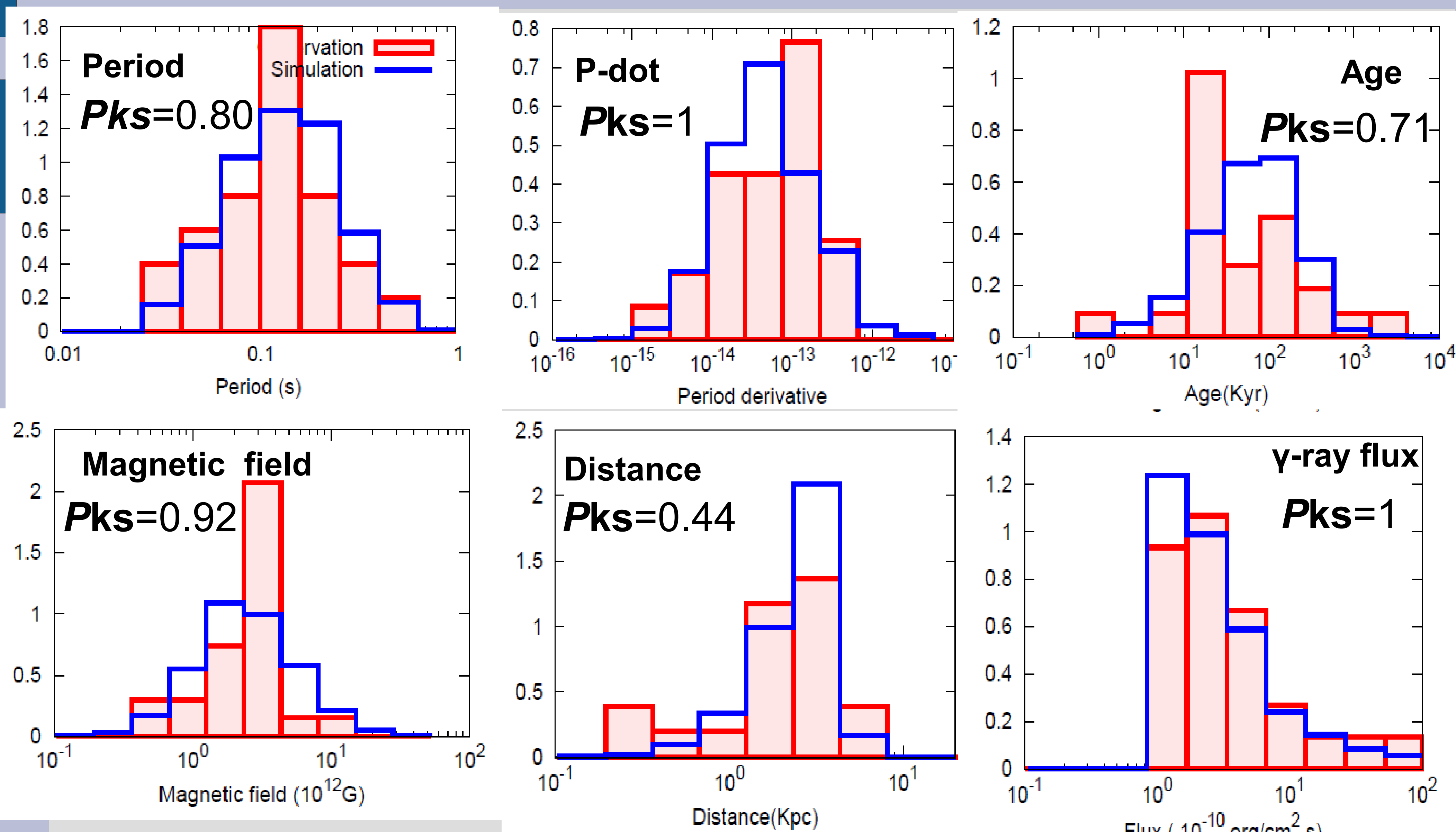
- Simulations ;

  Radio-selected; ~12

  γ-selected; ~15
- **The simulation predicts most of (or all) "bright" γ-ray pulsars have been discovered.**

Bright γ-ray pulsars (F>10^{-10} erg/cm^{2}s)

*P*ks; P value of Kolmogolov-Smirnov test

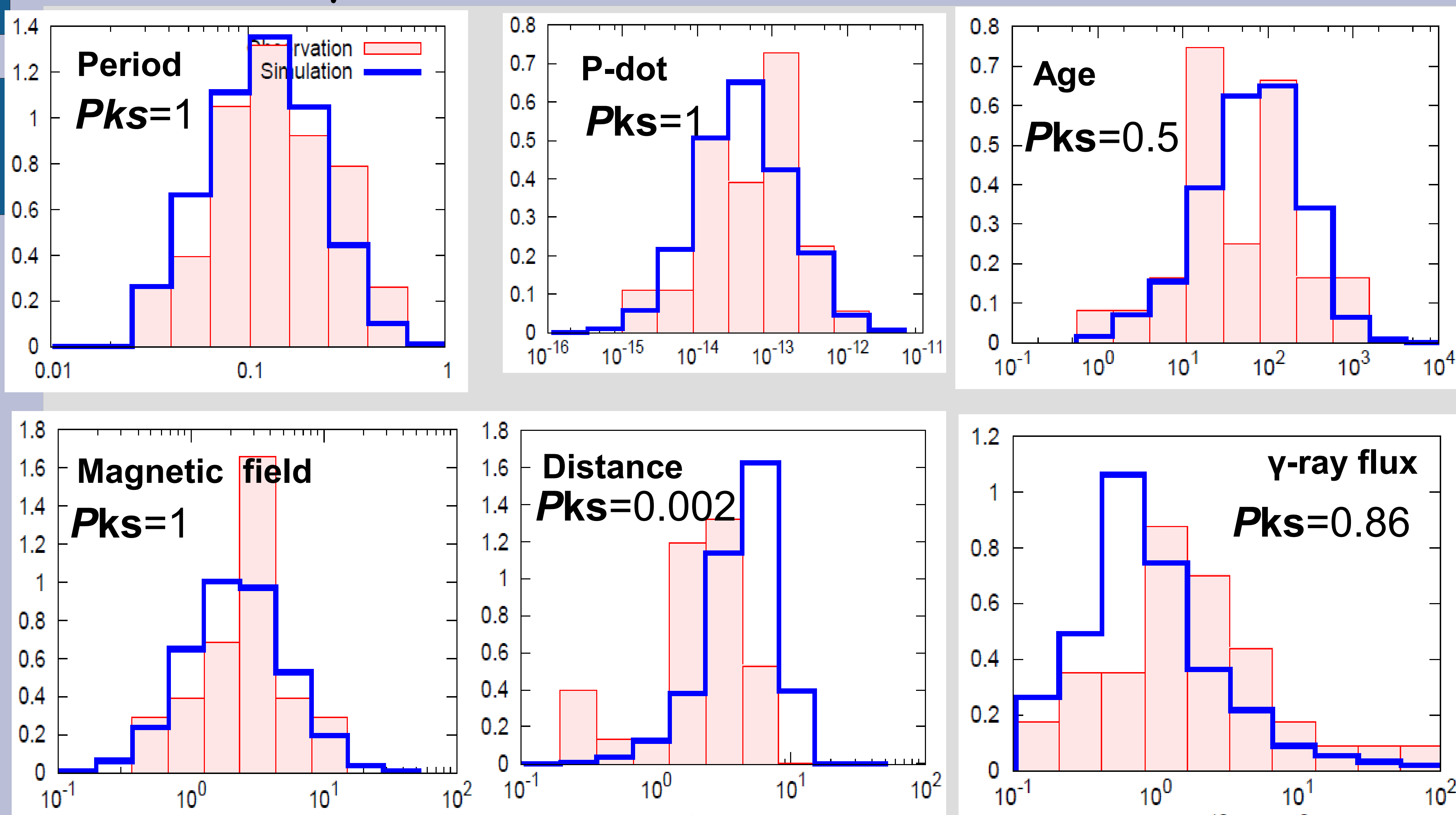


- We set the observed threshold energy flux at
(1) $F=10^{-11}$ erg/cm^{2}s for radio selected,
(2) $F=5\times 10^{-11}$ erg/cm^2 s for γ-selected,
which is the minimum flux in First catalog.

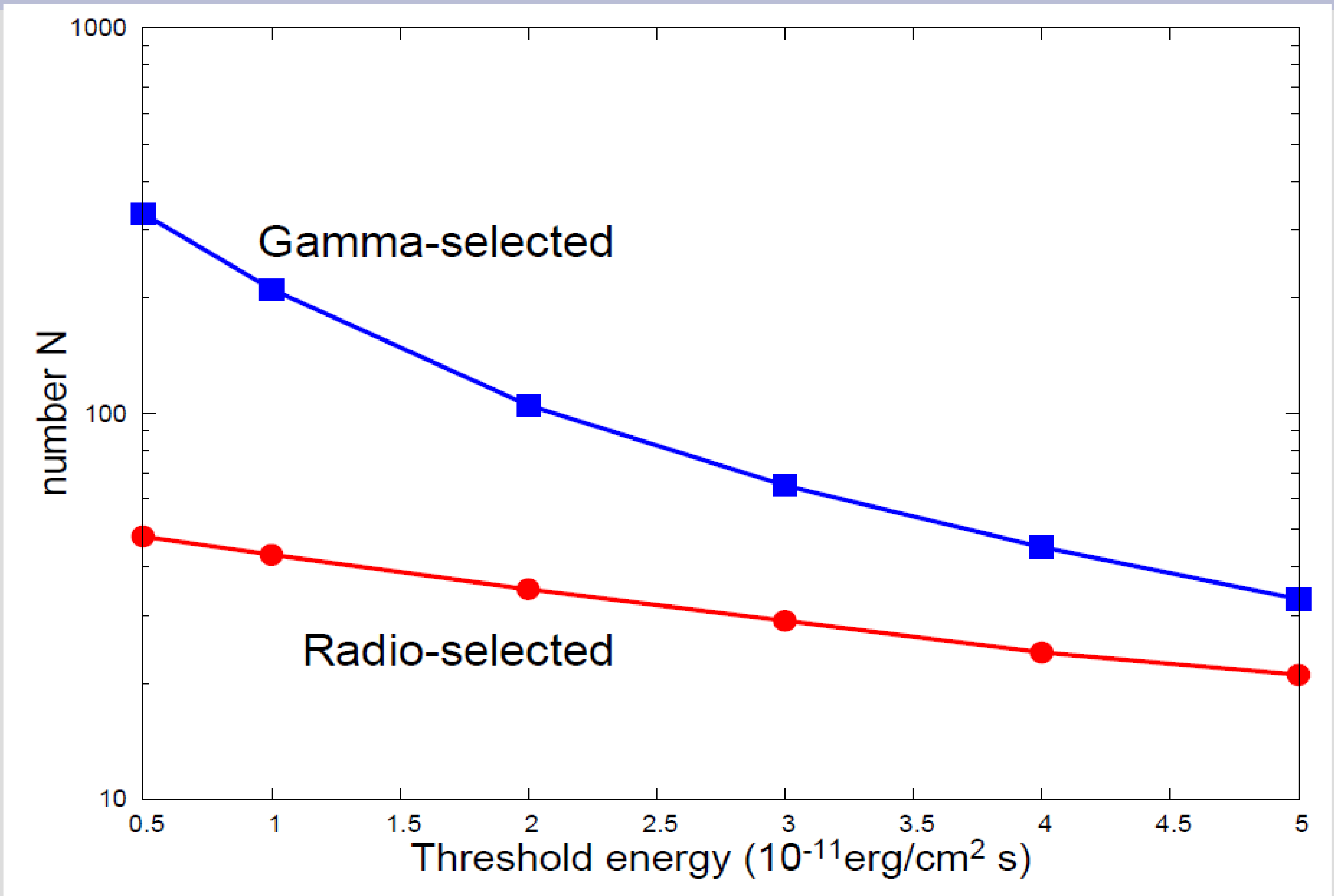
- Simulation predicts
(1) ∼42 for radio-selected
(2) ∼34 for γ-selected

Note; Fermi observations;
(1) 22 for radio-selected
(2) 17 for γ-selected

We expect more dim and distance γ-ray pulsars can be detected by Fermi.



- We can predict the number of the detectable γ-ray pulsars with threshold energy flux



Summary

- Population of observed γ-ray pulsars by *Fermi* were used to test our outer gap model.
- We perform a Monte-Carlo simulation
- The present model can explain the population of the bright γ-ray pulsars ($F>10^{-10}$ erg/cm2s)
- The model predicts more γ-ray pulsars can be detected by *Fermi*.
- It will be possible that more than 100γ-ray pulsars will be detected by *Fermi*

Simulation on Population synthesis of neutron star

- A Monte Carlo simulation on the neutron star (Sturner & Dermer 1996).
  1; The initial properties (position, velocity and surface magnetic field etc.) of new born neutron star are simulated using Monte Carlo method.
  2; Birth rate= 1-2 /century
  3; The current position is solved with Galactic potential.
- We select radio pulsars, radio-loud and radio-quiet γ-ray pulsars with emission models.